Research Article

Neuromechanical adaptations during a robotic powered exoskeleton assisted walking session

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Objective: To evaluate gait parameters and neuromuscular profiles of exoskeleton-assisted walking under Max Assist condition during a single-session for; (i) able bodied (AB) individuals walking assisted with (EXO) and without (non-EXO) a powered exoskeleton, (ii) non-ambulatory SCI individuals walking assisted with a powered exoskeleton.
Design: Single-session.
Setting: Motion analysis laboratory.
Participants: Four AB individuals and four individuals with SCI.
Interventions: Powered lower extremity exoskeleton.
Outcome Measures: Temporal-spatial parameters, kinematics, walking velocity and electromyography data.
Results: AB individuals in exoskeleton showed greater stance time and a significant reduction in walking velocity ($P < 0.05$) compared to non-EXO walking. Interestingly, when the AB individuals voluntarily assisted the exoskeleton movements, they walked with an increased velocity and lowered stance time to resemble that of slow walking. For SCI individuals, mean percent stance time was higher and walking velocity was lower compared to all AB walking conditions ($P < 0.05$). There was muscle activation in several lower limb muscles for SCI group. For AB individuals, there were similarities among EXO and non-EXO walking conditions however there were differences in several lower limb EMGs for phasing of muscle activation.
Conclusion: The data suggests that our AB individuals experienced reduction in walking velocity and muscle activation amplitudes while walking in the exoskeleton and moreover with voluntary control there is a greater temporal-spatial response of the lower limbs. Also, there are neuromuscular phasic adaptions for both AB and SCI groups while walking in the exoskeleton that are inconsistent to non-EXO gait muscle activation.

Keywords: Spinal cord injury, Powered exoskeleton assisted walking, Non-ambulatory SCI, Surface electromyography, Kinematics, Case series

Introduction

Spinal cord injury (SCI) can lead to loss of motor and sensory function that limits or restricts walking ability overground. Powered exoskeletons are robotic devices that are intended for rehabilitation, mobility and walking overground in those with SCI who otherwise have limited or no ability to walk.[1–3] To date two currently available devices have received U.S. Food and Drug Administration (FDA) clearance for home and community use,[4,5] and three have FDA approval for clinical use. Powered exoskeletons are envisioned as devices that could be used in the home and community and potentially improve mobility and independence. With continual use, the potential to maintain or improve benefits gained from rehabilitation programs becomes an important consideration, as do the immediate practical advantages of being able to perform upright activities of daily living. While the powered exoskeletons may have the capacity to function in walking mode for several hours, limited knowledge is

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available about their effect on the individuals' kinematics and neuromuscular system following acute or long-term use in subacute to chronic SCI.[6–8] Investigating locomotor responses in individuals after neurological lesions, when using the robotic devices, is fundamental to the development of improved rehabilitation strategies and to explore the mechanisms involved in changing or improving locomotor function.

The main purpose of this paper is to present preliminary single session locomotor data for eight individuals including four able bodied (AB) individuals and four individuals with a motor complete or incomplete SCI who have had various amounts of training using a powered exoskeleton. The AB individuals were observed under conditions of walking overground with and without the wearable device. All participants (SCI and AB) participated in a single session of testing to assess temporal-spatial, lower limb kinematic parameters, and associated lower limb muscle activation data during a series of walking trials.

Methods

This is a single-session cross-sectional study to evaluate gait parameters and neuromuscular profiles of exoskeleton-assisted walking under Max Assist condition for AB and SCI individuals walking assisted with and without (AB only) a powered lower extremity exoskeleton (Fig. 1). All procedures performed in this investigation were approved by the Kessler Foundation Institutional Review Board and informed consent was obtained prior to study participation from all participants.

Participants and assessment protocol

Prior to testing, the SCI individuals obtained training sessions to learn to use the exoskeleton lasting approximately 2 hours long and the frequency of 3 ± 1 sessions/week. Inclusion criteria for the SCI group were the following: able to tolerate upright standing for up to 30 minutes; had sufficient upper body strength to balance using the walker while wearing the exoskeleton; a height between 1.57 m and 1.88 m; weigh $\leq$100 kg. Exclusion Criteria included: joint contractures of extremities limiting range of motion (ROM) during walking with assistive devices; medical issue preventing full weight bearing and walking (e.g. orthopaedic injuries, pain, severe spasticity); skin issues that prevent wearing the device; any problems wearing an external device that supported the spinal column or the head, neck, or trunk; persistent problems with hypotension; had pressure sores adversely affecting weight bearing or proper fitting of exoskeleton, or interfering with therapist's assistance; pre-existing condition affecting ability to exercise; history of hospitalization for heart attack, heart surgery or acute heart failure within 3 months of enrolment in study; bone density measurement (as recorded by GE Lunar Prodigy, GE Healthcare, USA) for knee at or below 0.5755 gm/cm^2.[9] Clinical measures for the SCI individuals included manual muscle testing,[10–11] and clinical assessment of spasticity using the Modified Ashworth Scale.[12] Exclusion criteria for AB individuals included any conditions that affected their ability to walk in the powered exoskeletons.

Device description

The powered exoskeleton (Ekso™, Ekso Bionics, Richmond, CA, USA) used with all individuals has been described elsewhere.[8] All SCI individuals were trained and tested in Ekso™ (version 1.1) for Max Assist condition while the AB individuals were tested in EksoGT™ for Max Assist condition. The Max Assist setting provides the maximum amount of motor assistance to move the legs consistently through a predefined gait pattern and is less susceptible to the participant's interaction (Ekso GT™ Operating Manual Copyright© 2013 Ekso GT Bionics, Inc Part Number 103299 REV B1). The AB individuals received two sessions of training whereby they could walk using the powered exoskeleton with close supervision.

Experimental test conditions

After the respective training sessions, during testing the individuals with SCI were instructed to ambulate with their best effort in the powered exoskeleton while the AB individuals were asked to ambulate under five experimental conditions (Fig. 1). For conditions one, two and three the AB individuals walked independently without the powered exoskeleton (non-EXO): at their self-selected pace (SELF), fast pace (FAST) and slow pace (SLOW) respectively to assess the influence of walking velocity on temporal-spatial parameters and muscle activation profiles. During condition four the AB individuals ambulated with the powered lower extremity exoskeleton (EXO) without actively assisting the device or using minimal voluntary control where the exoskeleton provides 100% of the movements (PASSIVE$_{exo}$) and during condition five they voluntarily tried to contribute to the movements provided by the exoskeleton (ACTIVE$_{exo}$). All walking conditions using the exoskeleton for SCI and AB, including PASSIVE$_{exo}$ and ACTIVE$_{exo,}$ was performed under the Max Assist setting. Six to eight steps were captured for all individuals during all conditions while walking along a 10-meter walkway designated within the motion capture volume and repeated 2–4 times as needed within a 1 hour session. For all individuals, walking with the exoskeleton occurred with the use of an assistive device (bilateral crutches or walker) and with close supervision (no physical contact). The choice of the assistive device, whether bilateral crutches or walker, was dependent on the therapist and based on the individuals' ability to walk with the exoskeleton.

Kinematic data collection

Kinematic data were collected at 60 Hz using Vicon (Oxford Metrics, Oxford, UK) and Motion Analysis Corporation (Santa Rosa, CA, USA) systems. Reflective markers were placed on specific anatomical landmarks using adhesive tape including markers placed on the powered exoskeleton.

Electromyography data collection

Surface electromyography (sEMG) data were collected at 2520 Hz using the MA100 and MA300 systems (Motion Lab Systems, Baton Rouge, LA, USA). sEMG electrodes were placed on the following muscles bilaterally: gluteus maximus (GM), medial bicep femoris (BF), medial gastrocnemius (GN), soleus (S), rectus femoris (RF), vastus lateralis (VL) and tibialis anterior (TA). Location of the electrode placement has been explained elsewhere.[13] Ground electrodes were placed on the clavicles for providing a common reference. Prior to electrode placement, skin was prepared by shaving all hair, cleansing with 70% isopropyl alcohol and lightly abrading the skin.[14–15] Electrode preparation and placement was performed by the same examiner during all testing sessions to ensure repeatability and consistency of collected data.

Data reduction

Kinematic data were filtered using a second order low pass Butterworth filter with a cut-off frequency of 6 Hz. At least two bilateral gait cycles per trial were individually normalized to 100% of the gait cycle. The gait cycle was measured between consecutive heel strikes on the same foot and then averaged across all trials to generate the mean profiles. Temporal-spatial parameters (i.e. stance/swing phase and walking velocity) were derived from the kinematic data. Stance phase was defined as the time between heel strike and the subsequent toe off on the same foot. Walking velocity was calculated for each trial using the time taken to traverse the 10-meter walkway and later averaged across trials within each condition. All comparisons were performed on the normalized percent gait cycle data and represented as mean ± standard deviation.

The sEMG data were gain-normalized, full-wave rectified and filtered using a 2nd order Butterworth band-pass filter (20–150 Hz) for further analysis. The Teager-Kaiser energy operator (TKEO)[16–20] was applied to the sEMG signal for defining the onset and cessation of sEMG bursts. After defining the on-off bursts, the following measures were derived using custom programs written in MATLAB (MathWorks™, Natick, MA, USA): Burst duration (% gait cycle), mean amplitude (μV) and peak amplitude (μV).

Statistical analyses

Descriptive statistics for all variables includes mean and standard deviations for both SCI and AB individuals. For the AB group there was a one-way repeated measures ANOVA to compare walking conditions (SELF, FAST, SLOW, PASSIVE_{exo} and ACTIVE_{exo}) for dependent variables (mean walking velocity; temporal-spatial parameters; mean percent stance time and swing; mean knee and hip ROM). Between SCI group and AB group, a one-way ANOVA was applied to compare group differences for velocity, temporal-spatial and kinematic variables. In addition, for the AB group there was a one-way repeated measures ANOVA to compare walking conditions for EMG dependent variables (mean amplitude, peak amplitude and burst duration) for all muscles. Tukey *post hoc* tests were performed for all possible 2-way comparisons. Results were considered significant for $P < 0.05$.

Results

Four individuals with SCI and four AB individuals participated in this study (Table 1). Results are presented for four AB individuals (age 27.3±3.2 years, all males, height 1.8±0.1 m, weight 76.1±8.4 kgs) and four individuals with SCI (age 39.4±11.4 years, two males and two females, height 1.7±0.1 m, weight 79.1±12.3 kg) during a single session. Two of the four individuals with SCI (SCI1 and SCI3) were motor complete and two (SCI2 and SCI4) were motor incomplete and not participating in any regular exercise program. Number of training sessions, demographic information including spasticity measures for each participant are given in Table 1.

The experimental setup for all assessments is shown in Fig. 2 while a flowchart describing all the testing conditions are shown in Fig. 1. Temporal-spatial parameters, walking velocity and kinematic ROM data are presented in Fig. 3; sagittal kinematic profiles for the hip, knee and ankle are presented in Fig. 4A (AB – left leg only) and Fig. 4B (SCI) while the sEMG filtered full-wave rectified and root mean squared (RMS) profiles for the lower extremity muscles are shown in Fig. 5A (AB – left leg only) and Fig. 5B (SCI); sEMG definitions and outcome measures are presented for the lower extremity in Fig. 6.

Table 1A. Participant demographics (SCI).

Participant	Time Post Injury (yrs)	Neuro-logical Level	AIS	Upper/Lower Extremity Score	AIS Sensory Level	No. of Training Sessions
SCI1	0.5	T10	A	50/0	T10	5
SCI2	1.9	T10	C	50/11	T10	4
SCI3	0.6	T12	A	50/0	T8	30
SCI4	9.5	C5/6	C	14/16	C6	3

Table 1B. Exoskeleton settings for all participants.

	Able Bodied - EksoGT™				SCI – Ekso™ 1.1			
	AB1	AB2	AB3	AB4	SCI1	SCI2	SCI3	SCI4
Age (yrs)	26	26	25	32	27	38	49	53
Height (m)	1.9	1.8	1.7	1.8	1.6	1.8	1.7	1.8
Weight (kgs)	81.8	84.1	65.9	72.7	59.1	76.5	84	84.8
Ekso™ settings								
Step Length (in)	13.5	13.5	13.5	13.5	10	11	13	11
Step Height (in)	0.5	0.5	0.4	0.4	1	1	0.9	1
Swing Time (s)	1	1	1	1	1.3	1.3	1.3	1.3
Lateral Target*	-2	-2	-1	-1	1	1	-1	-1
Dorsiflexion^	2	0	0	0	NA	NA	NA	NA
Spring#	1	4	4	4	NA	NA	NA	NA
Assistive Device**	C	C	C	C	W	W	C	W

*Lateral Target
An adjustable point in space that the therapist can set to indicate when Ekso has reached a certain deviation laterally. Functionally, it is best designed to select the point to match the intended balance location for a user's center of gravity over his base of support for each foot.
^Dorsiflexion
Optimal standing balance point that allows for minimal upper extremity use in static stance (-3 to 2).
#Spring
Ankle Stiffness adjustments (1=least stiff, 4=most stiff), aids in single limb stance stability and balance assist.
**Assistive Device: C – Crutches; W – Walker
NOTE: All the above units are as per the adjustment settings relative to the device.

Temporal spatial parameters

The AB individuals showed slower mean walking velocity during the PASSIVE$_{exo}$ condition than the ACTIVE$_{exo}$ condition (0.25 ± 0.07 m/s vs 0.36 ± 0.05 m/s respectively; P = 0.001). Both of these conditions resulted in slower velocities than all other AB non-EXO walking conditions (Fig. 3B). Mean percent time of gait cycle in stance was greater for PASSIVE$_{exo}$ compared to the ACTIVE$_{exo}$ (79.6 ± 2.3% vs 70.6 ± 4.6% respectively; P = 0.0001) and all other non-EXO walking speeds (SS = 63.4 ± 2.9%; FAST = 58.8 ± 1.8%; SLOW = 65.2 ± 2.1%, Fig. 3A). No significant difference in percent time in stance phase between the ACTIVE$_{exo}$ and SLOW conditions was observed.

Table 1C Spasticity measures using the Modified Ashworth scale.

	Flexors		Extensors	
	R	L	R	L
SCI1				
Hip	0	0	0	0
Knee	0	0	0	0
Ankle	0	0	0	0
SCI2				
Hip	1+	0	1+	1
Knee	3	2+	2	3
Ankle	3	3	3	3
SCI3				
Hip	0	0	0	0
Knee	0	0	0	0
Ankle	0	0	0	0
SCI4				
Hip	1+	0	1+	1
Knee	1+	0	2	1
Ankle	1	0	0	1

The mean walking velocity (Fig. 3B) for the four SCI individuals was less than PASSIVE$_{exo}$ condition (0.13 ± 0.09 m/s vs 0.25 ± 0.07 m/s, P = 0.0001) and all other AB walking conditions. Mean percent stance time for individuals with SCI (86.8 ± 6.2%) was significantly greater than ACTIVE$_{exo}$ (70.6 ± 4.6%, P = 0.001) but not PASSIVE$_{exo}$ (79.6 ± 2.3%).

Kinematics

For AB individuals, the mean bilateral hip and knee ROM was lower for PASSIVE$_{exo}$ compared to ACTIVE$_{exo}$ conditions: 39.9 ± 3.7° vs 46.9 ± 6.3° for

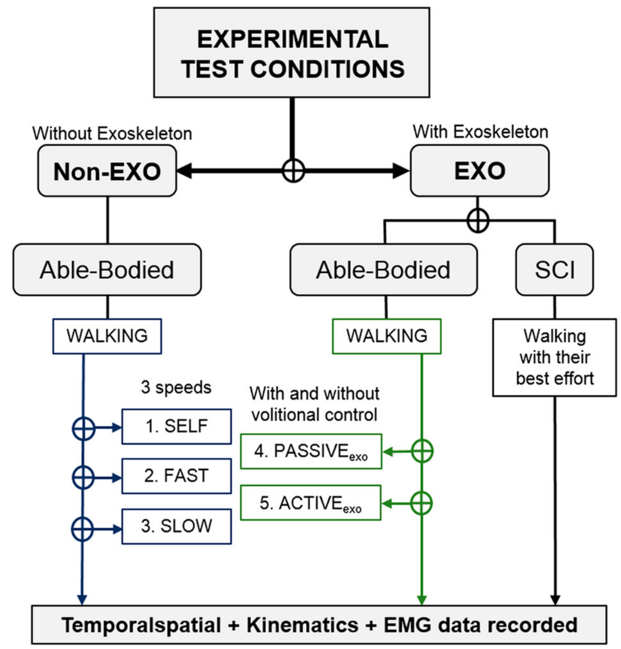

Figure 1 Experimental test conditions.

the hip and 55.1±3.8° vs 58.9±4.3° for the knee respectively. The mean bilateral hip and knee ROM for individuals with SCI was 46.2±5.4° and 55.9±5.7° respectively and were not significantly different from the AB walking conditions. For AB walking conditions there was an increase in hip ROM in the FAST condition compared to all other conditions ($P < 0.05$) whereas no significant differences were observed among conditions for average knee ROM.

Muscle activation sEMG data for AB individuals

The individuals in the AB group showed different sEMG profiles within their five walking conditions. The mean and peak amplitude for the gluteus maximus muscle for PASSIVE$_{exo}$ and ACTIVE$_{exo}$ are less than FAST condition only ($P = 0.0001$) but not significantly different from other conditions. For the bicep femoris, peak sEMG amplitude for ACTIVE$_{exo}$ was greater than both PASSIVE$_{exo}$ ($P = 0.05$) and slow walking ($P = 0.038$) conditions. Burst duration for ACTIVE$_{exo}$ was greater than FAST condition ($P = 0.03$) but not significantly different from any other conditions. For PASSIVE$_{exo}$ condition, the gastrocnemius peak amplitude was less than FAST condition ($P = 0.0042$). For anterior thigh muscles, rectus femoris and vastus lateralis mean amplitudes for PASSIVE$_{exo}$ and ACTIVE$_{exo}$ are less than FAST condition ($P < 0.05$). Peak amplitude was greater for FAST condition compared to all other conditions including PASSIVE$_{exo}$ and ACTIVE$_{exo}$ (Fig. 5A and 6B) for all muscles except the bicep femoris.

Muscle activation and kinematics for individuals with SCI

Mean and peak amplitude from sEMG activation were recorded for bilateral lower extremity muscles for both the complete (SCI1 and SCI3) and incomplete (SCI2 and SCI4) individuals with SCI (Fig. 6C). Although the kinematic profiles for hip and knee were similar for both motor incomplete SCI individuals (Fig. 4B), their bilateral sEMG patterns illustrated very different and inappropriate phasing of firing for several muscles of the lower limb during the entire gait cycle (Fig. 5B). The observed firing pattern for individuals with motor incomplete SCI were non-reciprocal (not presented) and showed very little activation for the TA during stance and pre-swing unlike the muscle activation profile for the AB individuals (PASSIVE$_{exo}$). This was especially evident for SCI4 and affected the ankle

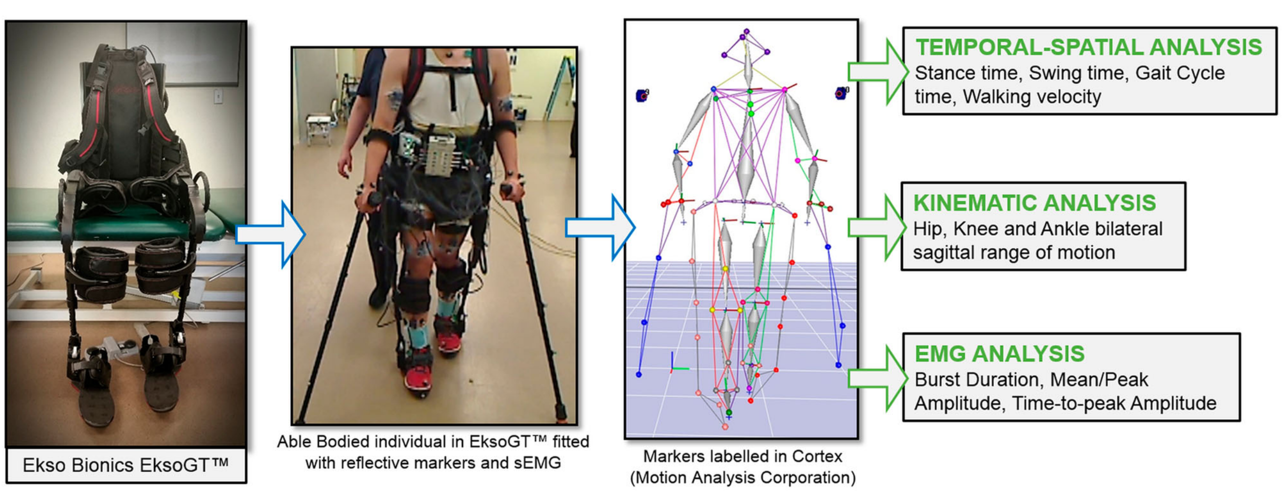

Figure 2 Experimental setup for motion capture data collection and analysis (temporal-spatial parameters, kinematics and EMG).

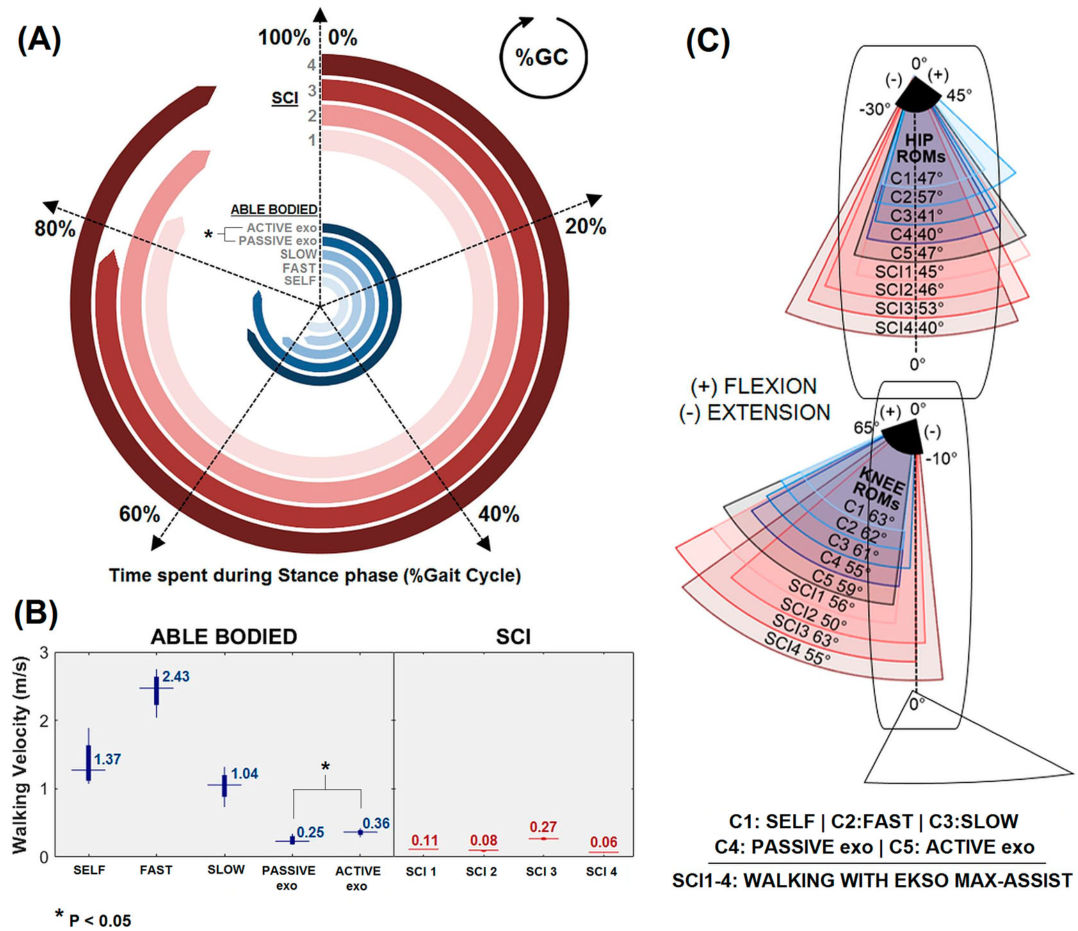

Figure 3 (A) Time spent during stance phase, (B) walking velocity and (C) hip and knee sagittal ROM from peak extension to peak flexion for AB (under various conditions, C1-C5) and SCI individuals (with Ekso^{TM} under max-assist).

kinematics (Fig. 4B). In addition, SCI4 shows co-contraction of the bilateral anterior and posterior thigh muscles (BF vs RF and BF vs VL agonist-antagonist muscle pairs for intralimb muscle activation) during walking (Fig. 5B). The lack of reciprocal muscle activation for both of these individuals with incomplete SCI was also reflected in the slower walking velocity compared to the other individuals. SCI3 who trained for the greatest number of sessions showed a reduction in the burst duration across all muscles (Fig. 6C).

Discussion

Temporal-spatial parameters for AB and SCI individuals

The evaluation for the AB temporal-spatial parameters while walking with the exoskeleton showed that there was a decrease in walking velocity, an increase in percent stance time, and decrease in percent swing time compared to walking independent without the wearable exoskeleton. However it is interesting to note that with more voluntary control (ACTIVE$_{exo}$), the stance and swing phase durations were not significantly different and even rather similar to the SLOW and SELF conditions. These results would suggest that with volitional input it is possible for the temporal-spatial parameters of the powered exoskeletons to resemble the independent non-EXO AB gait patterns for the same exoskeleton parameters. Furthermore for the PASSIVE$_{exo}$ where volitional input was suppressed, walking velocity, percent stance and percent swing variables are similar to the SCI group therefore reflecting that the lack of volitional input from both groups can affect the gait parameters.

There was a wide variation in the temporal-spatial parameters affecting gait velocity, and percent gait cycle in stance and swing across the SCI group. Experience with using the powered exoskeleton as well as level of completeness of the injury may have contributed to differences in the gait parameters. The walking velocity (Fig. 3B) for the two motor complete SCI individuals (SCI1: 0.11 ± 0.01 m/s and SCI3: 0.27 ± 0.03 m/s) showed that SCI3 with more experience (30 training sessions)

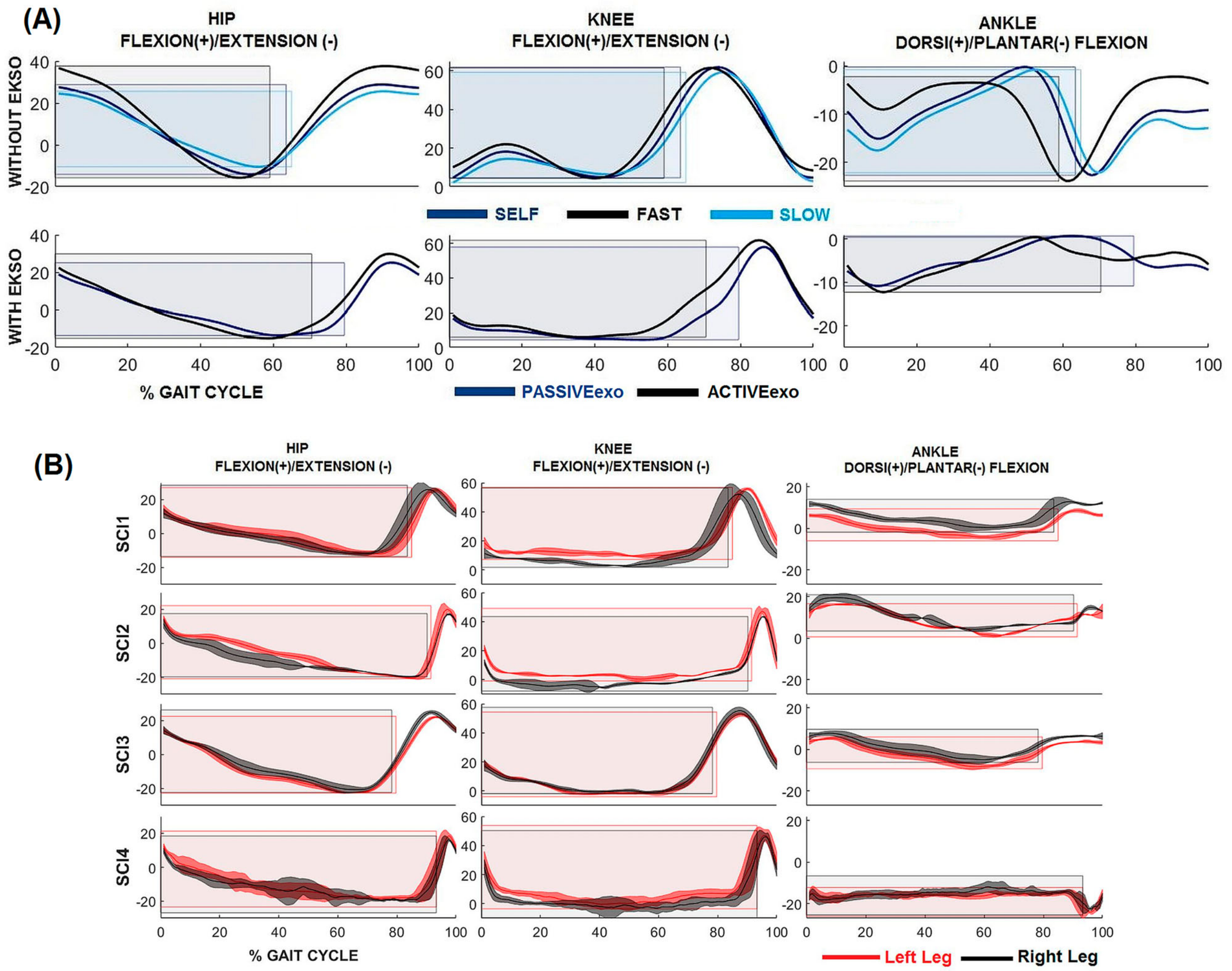

Figure 4 Ensemble-averaged sagittal kinematic profiles in degrees for (A) AB individuals (left-leg only) with and without exoskeleton, and (B) SCI individuals (same Y-axis scales used). Vertical line represents toe-off and horizontal line indicates peak amplitude on this figure and all subsequent plots.

walked faster and with a lesser amount of gait cycle time in stance compared to the SCI1 with less experience (5 training sessions; SCI1: 84.4 ± 1.0% and SCI3: 79.3 ± 1.1% time in stance; Fig. 3A).

Walking velocity is directed by the parameters set in the exoskeleton, slower velocities are also reflective of the large stance time required to translate the trunk to meet the required targets to initiate the subsequent step.[21] The individual who had more training hours (SCI3 > 30 training sessions) understandably decreased their overall stance and swing time to increase their overall walking velocity. More research with a larger sample size is needed to study the effects of longitudinal training on gait parameters.

With training, the lateral targets are adjusted to trigger with smaller lateral shifts as participants improved control of their weight shifts and balance leading to more efficient use of arms. An individual with less reliance or more efficient use of upper extremities for maintaining postural stability will be more proficient in using the device by providing necessary weight shifts while navigating with the device. An increase in stance time and reduction in walking velocity indirectly suggests that with SCI there would be neuromechanical changes that would be reflected in the temporal-spatial parameters. However, further research is needed to study the changes in the frontal plane and comprehensively evaluate the lateral weight shifts while using the device. In one of our recent studies, Ramanujam *et al.* [22] reported greater excursion of normalized center-of-mass (medial-lateral direction) which was centered about the mid-line after 5 hours per week over 20 weeks of training in EksoGT™ that provided evidence of a more efficient weight transfer strategy as well as improved dynamic stability in individuals with SCI.

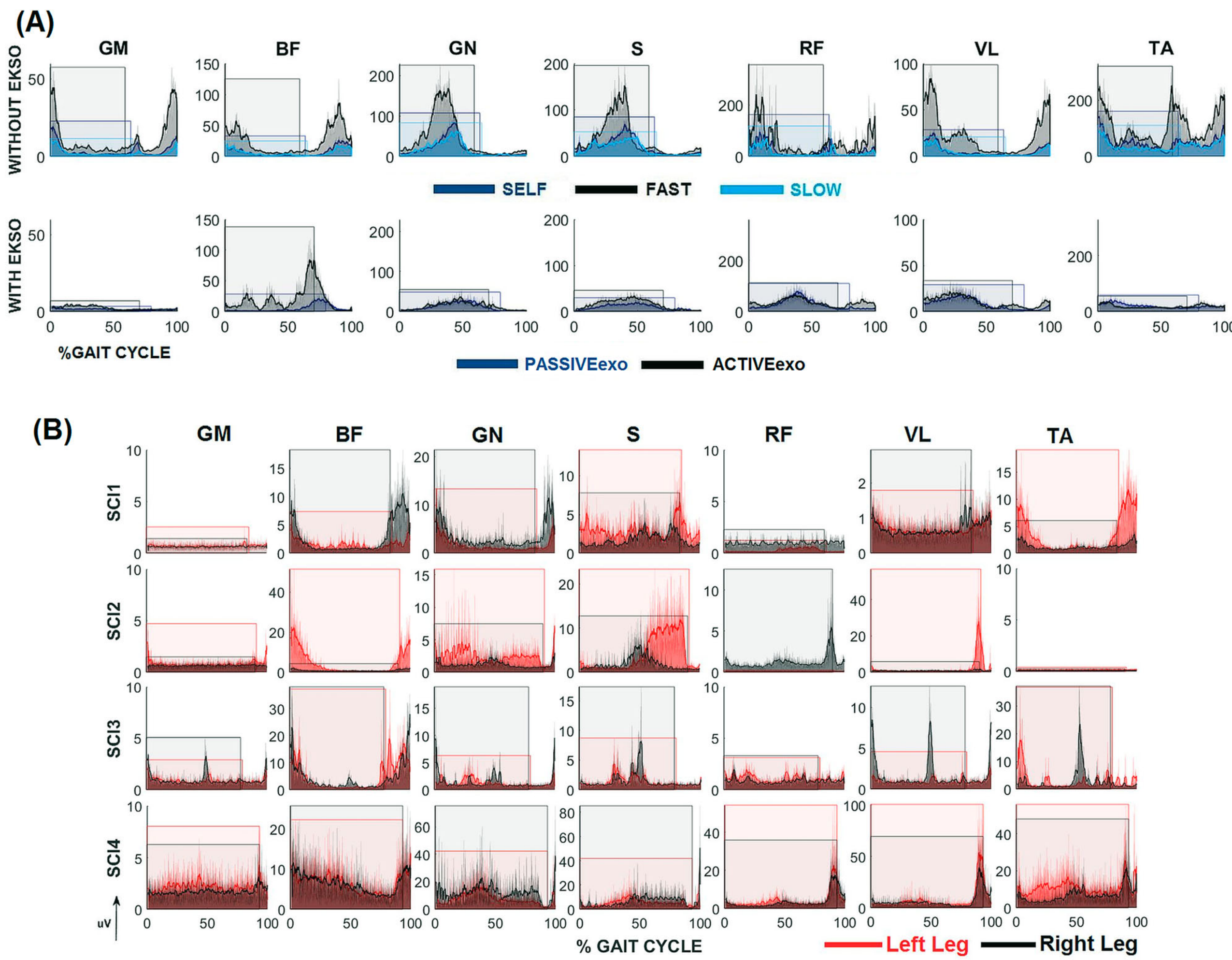

Figure 5 Mean filtered muscle activation (in μV) profiles of lower limb muscles for (A) AB individuals (left-leg only) with and without exoskeleton (same Y-axis scales used) and (B) SCI individuals (different scales used to visually preserve activation profiles). Solid lines represent the RMS profiles.

sEMG patterns for AB individuals

The AB group showed significant differences in the sEMG outcome measures for EXO conditions compared to non-EXO walking conditions. The burst duration was significant among several muscles, particularly those muscles associated with hip and knee motion, suggesting that the phasing of muscle activation within the wearable exoskeleton were different to walking independent of the exoskeleton. These differences in reciprocal firing patterns have been reported elsewhere[21] and hypothesized to be attributed to the different sensory inputs and biomechanical demands of stepping. For example when in the powered exoskeleton the participant may not be "fully" relaxed because the individuals needed to maintain the upper trunk posture and provide small lateral trunk displacements or excursions to trigger step transitions even though the limb movements were guided by the exoskeleton or potentially there was intermittent contact between the exoskeleton and the participant providing extraneous tactile input to the participant during gait.[21]

Due to sensory afferent input during stance phase foot loading, the gastrocnemius and soleus were actively firing for all conditions with and without the powered exoskeleton. Of note, the gastrocnemius and soleus muscles during foot loading in stance were actively firing during both exoskeleton conditions (ACTIVE$_{exo}$ and PASSIVE$_{exo}$) even though ankle joints of the exoskeleton are passive. The sEMG firing patterns and burst durations were similar to walking without the exoskeleton and were actively contributing to locomotion.[21] This was especially the case for the ACTIVE$_{exo}$ condition where there appears to be a greater amount of gastrocnemius and soleus activity during stance.

The bicep femoris and gluteus maximus were markedly different with higher amplitudes during the ACTIVE$_{exo}$ condition and may be best explained by the interruption of the normal activation of these muscle by the presence of "artificial forces" associated with the powered exoskeleton or by the "passive" contribution during loading caused by the important contribution of stretch reflexes in both of these muscles.[21,23] Several authors have suggested that the contribution of stretch to loading-related afferent inputs can directly elicit and affect the muscle activity during locomotion.[24–26] Consequently these ongoing repeatable reflex-related activities may be effective clinical rehabilitation strategies since there is a relationship between facilitation of segmental reflexes and recovery of walking.[27–29]

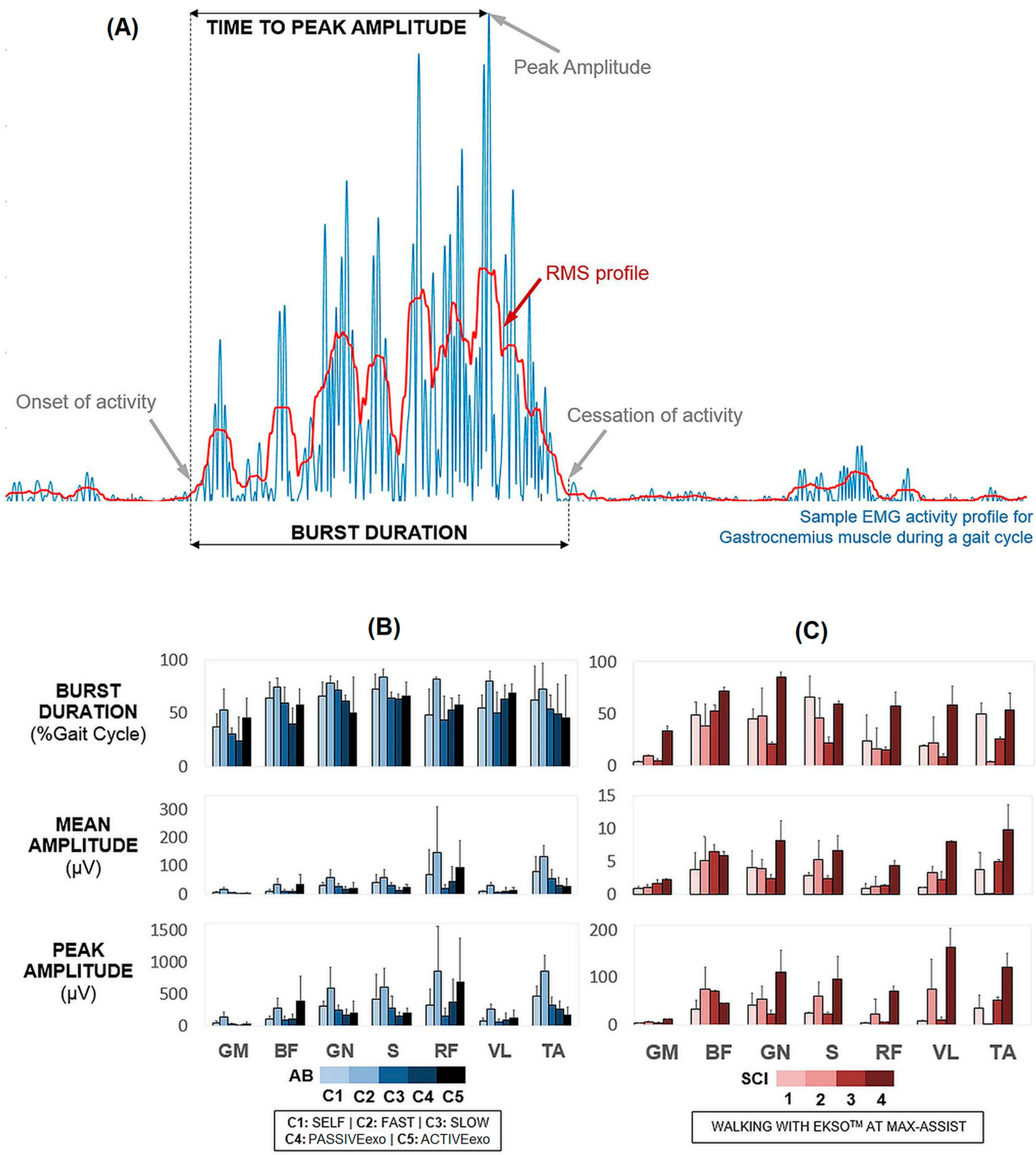

Figure 6 (A) Definitions of EMG outcome measures, (B) lower limb muscle activation parameters for AB individuals – left leg only and (C) bilateral lower limb muscle activation parameters for SCI individuals.

sEMG Patterns in individuals with SCI

The individuals in the SCI group showed similar sEMG profiles regardless of completeness of injury and amount of training in the exoskeleton. Most of the muscle activation was bilateral in the bicep femoris during terminal swing and some phasic activation in tibialis anterior and gastrocnemius/soleus muscles during stance. This suggests that the muscle activity is a contribution of muscle stretch or loading modulations in afferent patterns as inputs.[15]

Of note, an individual with a motor complete injury (SCI3) who completed the most training sessions, illustrated the least burst duration for the posterior muscles suggesting a potential neuromuscular adaption to the repetitive training. Previous research studies have reported that a combination of afferent stimuli during passive rhythmic and repeated movements of the lower limbs in combination with increased limb loading in both lower extremities during longitudinal training will induce neuromuscular plasticity even in an individual with motor complete SCI.[15,30]

Overall the muscle firing data suggests that neuromuscular activation adaptation patterns were reflected in individuals with SCI while walking in the exoskeleton. More research is required to investigate the effect on longitudinal training on gait parameters for both incomplete and complete SCI.

Limitations & future research

There were several limitations to our exploratory study. Although each group was tested under the same Max Assist condition, the able bodied group used EksoGT™ while the individuals with SCI were tested using Ekso™ (version 1.1). For the SCI group, there was variation in the time post injury, neurological level, and the number of training sessions before testing (Table 1). Depending on the ability of each individual, and as advised by the therapist, the individual either used a walker or bilateral crutches as an ambulation aid for walking with the exoskeleton. Future research should considering eliminating or at least minimizing many of these differences to strengthen the scientific merit in the research.

While the preliminary paper addressed measurement outcomes for a single testing session, the study's obvious next step is to evaluate the response of longitudinal training for changes in temporal-spatial parameters, neuromuscular and functional profiles for participants with SCI. In a recent study, our research team published findings from a longitudinal assessment of training in the powered exoskeleton (EksoGT™) for individuals with SCI.[22] Additionally, more research should be directed towards the specifics of the training protocol (frequency, dose, intensity) and the impact of how the different powered exoskeleton parameters contribute to training. Finally more research is needed to explore the effectiveness of the powered exoskeleton both as a compensatory orthotic device or a rehabilitation device for the improvement of independent walking as has been shown in other locomotor training research.[14,31–33]

Conclusion

The data presented in this paper suggests that our able bodied individuals experienced a reduction in walking velocity and muscle activation amplitudes while walking in the exoskeleton and moreover showed that with active volitional control there is a greater temporal-spatial response of the lower limbs. For the individuals with SCI there were neuromuscular responses particularly in the posterior lower limb muscle groups while walking in the powered exoskeleton. Importantly there were major differences for the four able bodied individuals between exoskeleton walking and independent walking without the exoskeleton related to the phasic firing patterns of several muscles particularly in the bicep femoris. More research with a greater sample population should examine these differences further for able bodied individuals walking in the exoskeleton under different device settings and importantly the longitudinal changes for individuals with motor complete and incomplete SCI.

Declaration of interest

The authors report no declarations of interest.

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